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A column generation technique for a crisis deployment planning problem.

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NAVAL POSTGRADUATE SCHOOL
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A COLUMN GENERATION TECHNIQUE FOR A
CRISIS DEPLOYMENT PLANNING PROBLEM

by

Newton Rodrigues Lima

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A Column Generation Technique For A Crisis Deployment Planning Problem

by

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requirements for the degree of

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ABSTRACT

This study is concerned with the problem of constructing an optimal military deployment plan for sealift assets during a period of conflict. The deployment problem is formulated as a set-partitioning optimization problem with a minimax objective. An algorithm for solving this problem is presented and it is based on solving a sequence of related, but simpler, linear programming problems by the column generation technique. The results of the model are ship schedules to meet the cargo requirements of the deployment plan in a minimum amount of time. Various implementation strategies are discussed as well as the occurrence of integer solutions. In addition, computational experiments for several small to medium size examples are presented.

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I. INTRODUCTION

A. PROBLEM STATEMENT

During a military deployment, troops, equipments and supplies must be transported from ports of embarkation to ports of disembarkation. Generally, the standard modes of transportation used in this operation are trucks, trains, airplanes and ships. Because of the limited amount of available resources and transport assets, planning becomes essential for a successful deployment. During peacetime, cargo transportation can be routinely scheduled and the normal criterion for a deployment plan is its cost (or operating expense). However, during a period of conflict (or crisis), expenses become secondary and it is more important to transport the troops and cargoes to their destinations as fast as possible.

This study restricts itself to the problem of constructing an optimal deployment plan which employs only sealift assets. Many of today's naval deployment plans are constructed manually and in an ad hoc manner. This process is quite time-consuming and does not guarantee to produce even a near optimal plan.

B. BACKGROUND

Research in deployment planning for both industrial and military applications has been concentrated on constructing deployment plans which minimize operating costs. In a survey article, Ronen [Ref. 1:pp. 119-126] describes the various modes of operation for cargo ships and provides a classification scheme for ship routing and scheduling models. In a more recent article, Brown et al. [Ref. 2:pp. 335-346] present and solve the crude oil tanker scheduling problem formulated as an elastic set-partitioning model.

On the military side, Goodman [Ref. 3] formulates the problem of scheduling the naval surface combatants of the Atlantic Fleet as a generalized set-partitioning problem. The resulting constraint matrices in both formulations of Brown et al. [Ref. 2] and Goodman [Ref. 3] have a large number of columns which must be generated beforehand and correspond to <u>all</u> feasible ship schedules. In a Naval Postgraduate School master's thesis, Collier [Ref. 4] formulates the deployment planning problem employing four standard modes of transportation as a linear programming problem, and solves it by the MPS III Mathematical Programming System developed by Ketron Management Science, Inc. [Ref. 5]. Related to Collier's study, Lally [Ref. 6] uses the General Algebraic Modelling System, GAMS [Ref. 7], to solve the problem of minimizing the number of sealift assets required to carry out a given deployment plan.

C. OBJECTIVE

In previous formulations of the deployment or ship scheduling problem, the primary objective is to minimize cost which is the most appropriate for peace-time military operations and for industry. This thesis addresses the same problem, but with a different objective: to minimize the duration of the deployment. In particular, it considers the construction of schedules for sealift assets to transport cargoes from their ports of origin to their ports of destination in the minimum length of time.

II. PROBLEM FORMULATION

To formulate the crisis deployment problem, the following data are assumed to be given:

1. The ports of embarkation and disembarkation for each cargo
2. The distances between ports
3. The number of ships with their speed
4. The compatibility between each ship and each cargo

When a ship is compatible with a cargo, we mean that the ship is compatible with both the cargo and its ports of embarkation and disembarkation. Therefore, in constructing the compatibility information one has to consider, for example, the ship and cargo type as well as the ship draft and the channel depth of both ports.

It is assumed that all cargoes are configured into full shiploads. This implies that when a ship picks up a given cargo, it must deliver it before any other cargo can be picked up. Therefore, the ship must travel to the port of disembarkation directly from the port of embarkation.

A. MATHEMATICAL FORMULATION

The problem of scheduling sealift assets in a crisis situation can be formulated as a variation of the standard set-partitioning model as follows.

Indices:

i - indexes shiploads of cargoes, where $i=1,2,...,m$ and m is the number of shiploads;

j - indexes ships, where $j=1,2,...,n$ and n is the number of ships available;

k - indexes a ship schedule.

Data:

S_{jk} - a binary vector representing the kth feasible schedule for ship j. The i^{th} component of S_{jk}, denoted by S_{ijk}, is:

$$S_{ijk} = \begin{cases} 1, & \text{if the } k^{th} \text{ feasible schedule for ship } j \text{ includes shipload } i; \\ 0, & \text{otherwise;} \end{cases}$$

t_{jk} - the completion time of schedule S_{jk}. (The calculation of t_{jk} is described in a numerical example below.)

Decision variables:

$$x_{jk} = \begin{cases} 1, & \text{if the } k^{th} \text{ feasible schedule for ship } j \text{ is selected for the deployment;} \\ 0, & \text{otherwise.} \end{cases}$$

Problem P1:

$$\min \left[\max \left(\sum_k t_{1k} * x_{1k} ,\ldots, \sum_k t_{nk} * x_{nk} \right) \right]$$

subject to:

$$\sum_{j=1}^{n} \sum_k S_{ijk} * x_{jk} \geq 1 \quad \text{for } i=1,\ldots,m \qquad (1)$$

$$\sum_k x_{jk} \leq 1 \quad \text{for } j=1,\ldots,n \qquad (2)$$

$$x_{jk} \in \{0,1\}.$$

The term $\Sigma_k \; t_{jk} * x_{jk}$ in the objective function represents the time for ship j to complete its assigned schedule. Therefore, max $\{ \Sigma_k \; t_{1k} * x_{1k} ,\ldots, \Sigma_k \; t_{nk} * x_{nk} \}$ represents the completion time of the longest schedule in the deployment plan. Since the deployment is considered completed only when all cargoes are delivered to their destinations, the completion time of the longest schedule becomes the length of the deployment plan, which is to be minimized. The first set of constraints in Problem P1 ensures that all cargoes are picked up by at least one ship and the second guarantees that at most one schedule is assigned to each ship.

In addition, the objective function of Problem P1 is a nonlinear convex function since it is a point-wise maximum

of a set of linear functions. However, Problem P1 can be transformed into a linear problem as follows.

Problem P2:

minimize z

subject to:

$$\sum_{j=1}^{n} \sum_{k} S_{ijk} * x_{jk} \geq 1 \quad \text{for } i=1,\ldots,m;$$

$$\sum_{k} x_{jk} \leq 1 \quad \text{for } j=1,\ldots,n;$$

$$z - \sum_{k} t_{jk} * x_{jk} \geq 0 \quad \text{for } j=1,\ldots,n;$$

$$x_{jk} \in \{0,1\}.$$

Note that the last set of constraints defines the objective function of Problem P1.

B. AN EXAMPLE

To illustrate the above integer programming formulation, consider the deployment problem depicted in Figure 2.1. There are two ships, Ship 1 and Ship 2, available for the deployment. Initially, Ship 1 is docked at Port P1 and Ship 2 at Port P2. There are 3 shiploads whose ports of embarkation and disembarkation are given in Table 2.1. Assume that both ships are compatible with all

ports and cargoes. The lines connecting various ports in Figure 2.1 represent possible movements between ports. The

TABLE 2.1

A LIST OF POE AND POD FOR THE SHIPLOADS

SHIPLOAD	POE	POD
1	1	1
2	2	1
3	3	2

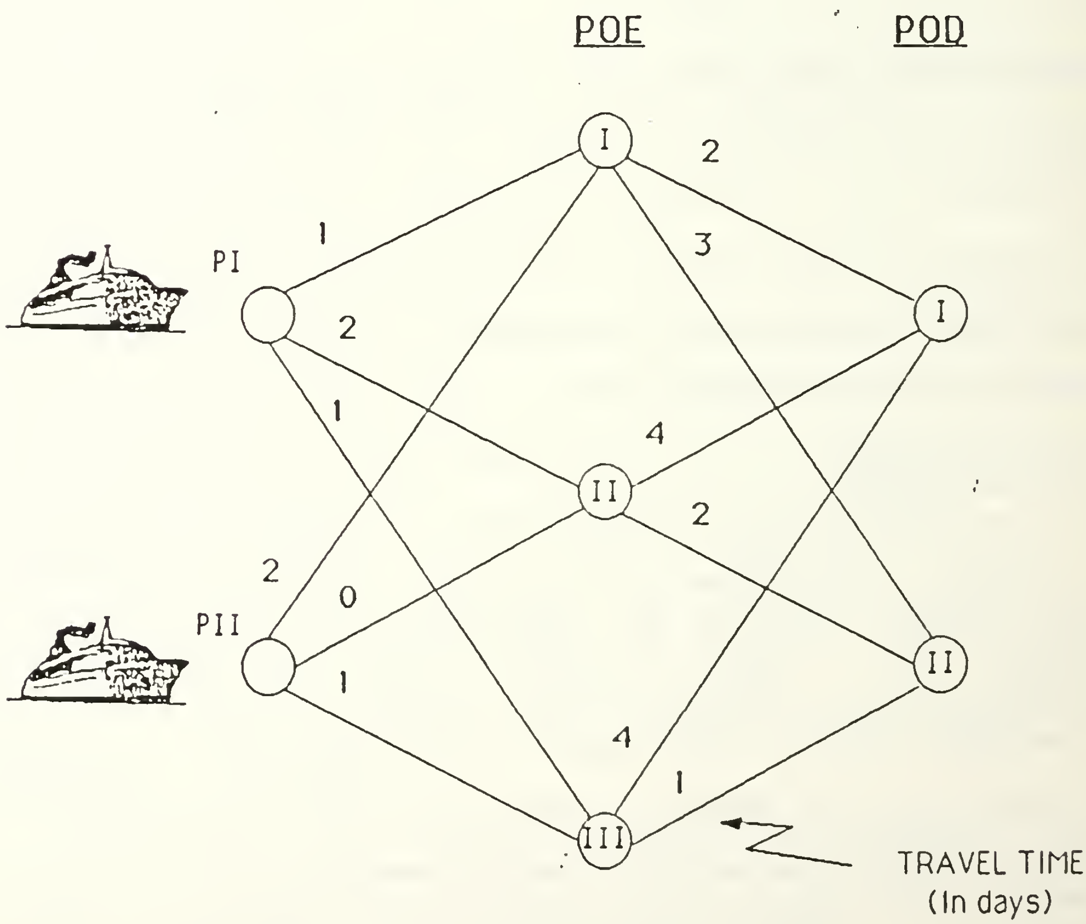

Figure 2.1 Data for the Deployment Problem

numbers adjacent to the lines represent the travel times for both ships, i.e., they have the same speed (assumed constant regardless of cargo loading).

Consider a schedule for Ship 1 which includes picking up cargoes 1 and 3. The binary vector representing this schedule has 3 components (since there are 3 shiploads) with the first and the third components having the value one and the second component the value zero. To carry out this schedule, Ship 1 can use one of the two possible routes: one which picks up cargo 1 first and then cargo 3 and the other which picks up the cargoes in the reverse order. Using the time given in Figure 2.1, the first route requires 8 days to complete and the second requires only 7 days. Since the objective is to minimize the completion time of the longest schedule, the completion time of 7 days is assigned to this schedule, i.e., $t_{14} = 7$. In general, the completion time t_{jk} is the time for ship j to carry out schedule k using the shortest route. Tables 2.2 and 2.3 display all possible schedules along with their completion times for Ships 1 and 2, respectively. Note that the schedule discussed above is the schedule S_{14} in Table 2.2.

The optimal deployment plan for this example consists of two schedules: S_{12} for Ship 1 and S_{24} for Ship 2, and requires 7 days to complete. In terms of decision variables, x_{12} and x_{24} equal one and all other variables equal zero.

The explicit formulation of the above example is given in Figure 2.2.

TABLE 2.2

POSSIBLE SCHEDULES FOR SHIP 1

	SCHEDULES						
	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}
COMPLETION TIME (IN DAYS)	3	6	2	7	10	8	12
SHIPLOAD 1	1	0	0	1	1	0	1
SHIPLOAD 2	0	1	0	0	1	1	1
SHIPLOAD 3	0	0	1	1	0	1	1

TABLE 2.3

POSSIBLE SCHEDULES FOR SHIP 2

	SCHEDULES						
	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}	S_{27}
COMPLETION TIME (IN DAYS)	4	4	2	7	8	8	12
SHIPLOAD 1	1	0	0	1	1	0	1
SHIPLOAD 2	0	1	0	0	1	1	1
SHIPLOAD 3	0	0	1	1	0	1	1

minimize z

subject to:

$$
\begin{array}{lr}
x_{11}+x_{14}+x_{15}+x_{17}+x_{21}+x_{24}+x_{25}+x_{27} & \geq 1 \\
x_{12}+x_{15}+x_{16}+x_{17}+x_{22}+x_{25}+x_{26}+x_{27} & \geq 1 \\
x_{13}+x_{14}+x_{16}+x_{17}+x_{23}+x_{24}+x_{26}+x_{27} & \geq 1 \\
x_{11}+x_{12}+x_{13}+x_{14}+x_{15}+x_{16}+x_{17} & \leq 1 \\
x_{21}+x_{22}+x_{23}+x_{24}+x_{25}+x_{26}+x_{27} & \leq 1 \\
z - [\, t_{11}*x_{11}+t_{12}*x_{12}+t_{13}*x_{13}+t_{14}*x_{14}+t_{15}*x_{15}+t_{16}*x_{16}+t_{17}*x_{17} \,] & \geq 0 \\
z - [\, t_{21}*x_{21}+t_{22}*x_{22}+t_{23}*x_{23}+t_{24}*x_{24}+t_{25}*x_{25}+t_{26}*x_{26}+t_{27}*x_{27} \,] & \geq 0
\end{array}
$$

$$x_{11},\ x_{12},\ x_{13},\ x_{14},\ x_{15},\ x_{16},\ x_{17} \ \varepsilon\ \{0,1\}$$

$$x_{21},\ x_{22},\ x_{23},\ x_{24},\ x_{25},\ x_{26},\ x_{27} \ \varepsilon\ \{0,1\}$$

Figure 2.2 A Formulation Of The Example Problem

III. A SEQUENTIAL SOLUTION TECHNIQUE

The solution procedure presented below addresses Problem P1 (and P2) indirectly. This procedure takes advantage of the fact that there exists a simpler problem which is related to Problem P1 (and P2). By sequentially solving a number of these simpler problems, one can arrive at a solution to Problem P1 (and P2).

A. A RELATED PROBLEM

In certain situations, it is not so critical that the planner obtains a deployment with the minimum duration. Instead, the duration of the deployment, say τ days, has been set by the top command and the planner only has to find a feasible plan which can be completed within this given length of time. To formulate this problem, define:

$$K_j(\tau) = \{\ k : S_{jk} \text{ is a feasible schedule for ship } j \text{ and } t_{jk} < \tau\ \},$$

That is, $K_j(\tau)$ is the set of schedules for ship j which can be completed within τ days. Then, we have the following problem which we refer to as the feasibility-seeking problem.

Problem P3(τ):

$$\min \sum_{i=1}^{m} w_i$$

subject to:

$$w_i + \sum_{j=1}^{n} \left(\sum_{k \varepsilon K_j(\tau)} S_{ijk} * x_{jk} \right) \geq 1 \quad \text{for all } i=1,\ldots,m;$$

$$\sum_{k \varepsilon K_j(\tau)} x_{jk} \leq 1 \quad \text{for all } j=1,\ldots,n;$$

$$w_i \, , \, x_{jk} \; \varepsilon \; \{0,1\}.$$

where w_i is an auxiliary variable to indicate whether or not shipload i will be left undelivered by the deployment plan. If the optimal solution to Problem P3(τ) is greater than zero, it means that τ is infeasible. In this case, one or more shiploads must be left undelivered or additional assets are required to obtain a plan which can be completed in τ days or less. Thus, if τ is a feasible duration, Problem P3(τ) will produce a feasible plan.

Note that Problem P3(τ) is parameterized by τ. If the minimum duration for a deployment plan, τ^*, is known, then the solution to Problem P3(τ^*) solves Problem P1 (and P2) as well. Otherwise, by varying τ and resolving Problem P3(τ) in a systematic manner, one can obtain a solution to Problem P1 (and P2). A strategy for searching for the minimum feasible duration τ^* is discussed in Chapter IV.

To illustrate the feasibility-seeking problem, consider the deployment problem presented in Chapter II. Assume that the planner is told to construct a plan with a duration of 8 days.

Then,

$K_1(8) = \{ 1, 2, 3, 4, 6 \}$ and

$K_2(8) = \{ 1, 2, 3, 4, 5, 6 \}$,

that is, the eligible schedules for this plan with a completion time of 8 days or less are those listed Tables 3.1 and 3.2. In this case, the optimal objective function value for Problem P3(8) is zero, because 8 days is a feasible duration. Each of the following pairs of schedules for Ships 1 and 2: (S_{11},S_{26}), (S_{12},S_{24}), (S_{13},S_{25}), (S_{14},S_{22}), and (S_{16},S_{21}), constitutes a deployment plan that can be completed within 8 days.

Similarly, if one solves Problem P3(τ) with τ equal to 7 days (the optimal duration), the optimal objective function value is still zero, and the pairs (S_{12},S_{24}) and (S_{14},S_{22}) are the only feasible deployment plans.

B. A COLUMN GENERATION APPROACH TO THE FEASIBILITY-SEEKING PROBLEM

Since the feasibility-seeking problem searches for a feasible deployment plan and does not have a real objective function to optimize, one expects that the relaxation of the integrality restriction would not produce fractional

solutions too often. This observation is corroborated by the computational result presented in Chapter IV in which integer solutions are obtained for over 90 per cent of the problems. Henceforth, we treat Problem P3(τ) as a linear programming problem.

As a linear program, Problem P3(τ) has many columns. To avoid generating these columns a priori, we apply the column generation technique, i.e., the Dantzig-Wolfe decomposition method [see, e.g., Ref. 8], to Problem P3(τ), and the following decomposed system is obtained.

TABLE 3.1

ELIGIBLE SCHEDULES FOR SHIP 1 WHEN τ=8

	SCHEDULES				
	S_{11}	S_{12}	S_{13}	S_{14}	S_{16}
COMPLETION TIME (IN DAYS)	3	6	2	7	8
SHIPLOAD 1	1	0	0	1	0
SHIPLOAD 2	0	1	0	0	1
SHIPLOAD 3	0	0	1	1	1

TABLE 3.2

ELIGIBLE SCHEDULES FOR SHIP 2 WHEN τ=8

	SCHEDULES					
	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}
COMPLETION TIME (IN DAYS)	4	4	2	7	8	8
SHIPLOAD 1	1	0	0	1	1	0
SHIPLOAD 2	0	1	0	0	1	1
SHIPLOAD 3	0	0	1	1	0	1

<u>Master Problem (MP)</u>:

$$\min \sum_{i=1}^{m} w_i$$

subject to:

$$\sum_{j=1}^{n} \sum_{k \varepsilon L_j(\tau)} S_{ijk} * x_{jk} + w_i \geq 1 \quad \text{for } i=1,\ldots,m \quad (1)$$

$$\sum_{k \varepsilon L_j(\tau)} x_{jk} \leq 1 \quad \text{for } j=1,\ldots,n \quad (2)$$

$$0 \leq x_{jk} \leq 1 \quad \text{for all } j, k.$$

<u>Subproblem for ship j (SP1(j))</u>:

$$k' = \arg \min_{k \varepsilon K_j(\tau)} \{ v_j + \sum_{i=1}^{m} S_{ijk} * u_i \}$$

where u_i is the dual variable corresponding to constraint set (1), i.e., the cargo (shipload) constraints, and v_j is the dual variable corresponding to the constraint set (2), i.e., the ship constraints. We refer to u_i as the i^{th} cargo dual and v_j as the j^{th} ship dual.

The column generation technique starts with an initial set of feasible schedules, $L_j(\tau)$, for each ship j. This initial set $L_j(\tau)$ may be an empty set. The master problem is solved and the dual variables u_i and v_j are obtained. From this set of cargo and ship duals, one or more subproblems are solved thereby generating additional schedules (columns), $S_{jk'}$, which are subsequently added to the set $L_j(\tau)$. The master problem is then resolved with the additional schedules (columns) and the new cargo and ship duals are obtained. The cycle then continues until the objective function value of Problem SP(j) is nonnegative for all j, i.e., all schedules have nonnegative reduced cost. This signifies that optimality is achieved. Figure 3.1 illustrates the cycling between the master and subproblem in the column generation technique.

As stated above, the subproblem is unnecessarily hard. In theory, it is not necessary to add schedules (columns) with the most negative reduced cost to the master problem. Any schedules (columns) with negative reduced cost would suffice. The following subproblem produces negative reduced cost schedules for the master problem.

Master Problem

$$\text{minimize} \quad \sum_{i=1}^{m} w_i$$

subject to:

$$\sum_{j=1}^{n} \sum_{k \varepsilon L_j(\tau)} S_{ijk} * x_{jk} + w_i \geq 1, \text{ for } i=1,\ldots,m$$

$$\sum_{k \varepsilon L_j(\tau)} x_{jk} \leq 1, \text{ for } j=1,\ldots,n$$

$$0 \leq x_{jk} \leq 1$$

The subproblem produces a new column, $S_{jk'}$, for the master problem, i.e., $S_{jk'}$ is added to $L_j(\tau)$.

The master problem produces cargo and ship duals for the subproblem.

Subproblem

$$k' = \arg \min_{k \varepsilon K_j(\tau)} \{ v_j + \sum_{i=1}^{m} S_{ijk} * u_i \}$$

Figure 3.1 - The Column Generation Technique.

Subproblem SP2(j):

For ship j find an index k' such that $k' \in K_j(\tau)$ and

$$v_j + \sum_{i=1}^{m} S_{ijk} * u_i < 0.$$

If k' solves Problem SP2(j), k' is an acceptable schedule. For details concerning the generation of acceptable schedules, the reader is referred to a related Master's Thesis by LCdr Svein Buvik [Ref. 9].

IV. IMPLEMENTATION AND COMPUTATIONAL RESULTS

To implement the column generation procedure we modified the revised simplex code described in Ref. 10, to solve the master problem. In this modification, we allow the algorithm to restart from the last optimal solution after one or more new schedules (columns) have been added to the master problem. Since the set partitioning problem is usually degenerate, we also reinvert the basis at every ten iterations. As for the subproblem, we employ the algorithm developed by Buvik [Ref. 9]. Both the master and subproblem algorithms are written in FORTRAN 77 and compiled by the IBM VS FORTRAN compiler. All runs were performed on an IBM 3033 AP computer at the W.R. Church Computer Center of the Naval Postgraduate School.

A. PROBLEM DATA

For our experimentation below, we consider the deployment scenario in which cargoes must be moved from the ports along the east coast of United States to ports in Europe. Table 4.1 lists approximate distances between various ports. The number of shiploads for our deployment problems are varied between 5 and 50 and the list of all 50 shiploads along with their POE's and POD's are given in Table 4.2. The number of ships assigned to the deployment are assumed to be between 2 and 30 ships and the initial

location of all 30 ships are given in Table 4.3. The speed of all 30 ships are between 18 and 25 knots, and on the average a ship is compatible with 75 % of the shiploads.

TABLE 4.1

DISTANCES BETWEEN PORTS
(IN NAUTICAL MILES)

PORTS	Ham.	Wilh.	Rot.	Antw.	Chb.
N. Y.	4030	3950	3790	3775	3520
Norf.	4340	4260	3490	4075	3800
Charl.	3650	4560	5390	4370	4090
Jax.	4850	4770	3470	4570	4280
Pens.	5390	3460	5125	5110	4820

where

N.Y. = New York

Norf. = Norfolk

Charl. = Charleston

Jax. = Jacksonville

Ham. = Hamburg

Wilh. = Wilhemshaven

Rot. = Rotterdam

Antw. = Antwerpen

Chb. = Cherbourg

Pens. = Pensacola

TABLE 4.2

LIST OF SHIPLOADS

SHIPLOAD	POE	POD	SHIPLOAD	POE	POD
1	1	1	26	3	1
2	2	1	27	3	3
3	1	3	28	3	5
4	2	2	29	3	4
5	3	2	30	3	1
6	3	1	31	3	5
7	1	4	32	4	2
8	3	4	34	4	1
9	1	5	34	4	2
10	2	5	35	4	4
11	2	1	36	4	2
12	4	1	37	4	5
13	2	1	34	4	3
14	2	2	34	4	3
15	3	2	40	4	4
16	2	3	41	4	4
17	2	2	42	4	5
18	2	4	43	4	5
19	2	3	44	4	5
20	2	5	45	5	3
21	2	3	46	5	3
22	3	2	47	5	4
23	3	1	48	5	4
24	3	2	49	5	1
25	3	4	50	5	5

POE

1. New York
2. Norfolk
3. Charleston
4. Jacksonville
5. Pensacola

POD

1. Hamburg
2. Wilhelmshaven
3. Rotterdam
4. Antwerpen
5. Cherbourg

TABLE 4.3

INITIAL DISTANCES BETWEEN SHIPS AND PORTS

(IN NAUTICAL MILES)

SHIP #	N.Y.	Norf.	Chb.	Jax.	Pens.
1	154	245	550	720	1190
2	100	255	450	620	290
3	250	945	650	1120	890
4	300	340	560	740	1890
5	250	320	990	2900	1440
6	100	390	650	720	3290
7	245	120	300	475	975
8	245	230	300	475	975
9	200	200	400	600	1100
10	600	600	700	900	1400
11	150	100	400	575	1075
12	350	95	200	375	875
13	550	110	540	165	700
14	550	300	120	165	700
15	800	758	700	750	1100
16	450	200	100	265	900
17	350	270	300	350	750
18	1240	1100	1000	1100	1500
19	720	475	165	90	640
20	720	475	165	280	600
21	1107	1500	900	905	1200
22	920	675	365	200	400
23	450	350	300	400	800
24	1350	1250	1200	1200	1600
25	1190	975	700	600	2230
26	1190	975	700	600	2140
27	890	675	400	300	300
28	1290	1075	800	700	300
29	900	700	500	400	600
30	1090	875	600	500	100

B. STRATEGIES FOR GENERATING SCHEDULES

As described in Chapter III, the decomposition process iteratively solves the master and subproblem in sequence. After having just solved the master problem, the subproblem obtains the cargo and ship duals from which it generates one or more negative reduced cost columns. At this point, there are several possibilities regarding the ship(s) for which the subproblem should generate schedules (or columns). The first obvious strategy is to generate a schedule for Ship 1 in the first iteration, a schedule of Ship 2 in the second iteration and so on until a schedule for each ship has been generated. At which point, the cycle of generating schedules (columns) begins again with Ship 1. The second strategy is to generate schedules for ship in the descending order of the ship duals, and the third strategy is just the reverse of the second strategy, i.e., generates schedules in the ascending order of the ship duals. The other strategy, which has been considered and soon after discarded, generates schedules for all ships during each iteration. This strategy tends to generate the same schedule for all ships, which seems redundant since no two ships can have the same schedule at optimality. In fact, there must exists a solution in which no two ships are assigned to pick up the same shipload. Based on this observation and preliminary experiments, the last strategy is discarded.

To compare the three strategies discussed above, we solved three feasibility-seeking problems at various lengths of deployment, τ. The first problem has 30 shiploads and 20 ships, the second problem has 35 shiploads and 20 ships, and the last has 40 shiploads and 20 ships. In Figure 4.1, we plotted the average cpu times on these three problems against the length of deployment. The first and third strategies clearly dominate the second.

C. SOLVING THE MINIMAX PROBLEM

As mentioned in Chapter III, one can solve the minimax problem by sequentially solving the feasibility-seeking problem in the following manner. First, pick an initial value for τ and then solve the feasibility-seeking problem at this value τ. If the optimal objective function is zero, then the value of τ is decreased and the feasibility-seeking problem is resolved at the new value. Otherwise, the optimal objective function is positive, the value for τ is increased and the feasibility-seeking problem is resolved.

The efficiency of the above algorithm is clearly a function of the initial value for τ. If the initial value for τ is close to the optimal, the feasibility-seeking problem has to be solved less often. Thus, it is important that a good initial value for τ is used to start the process of increasing and decreasing the value τ.

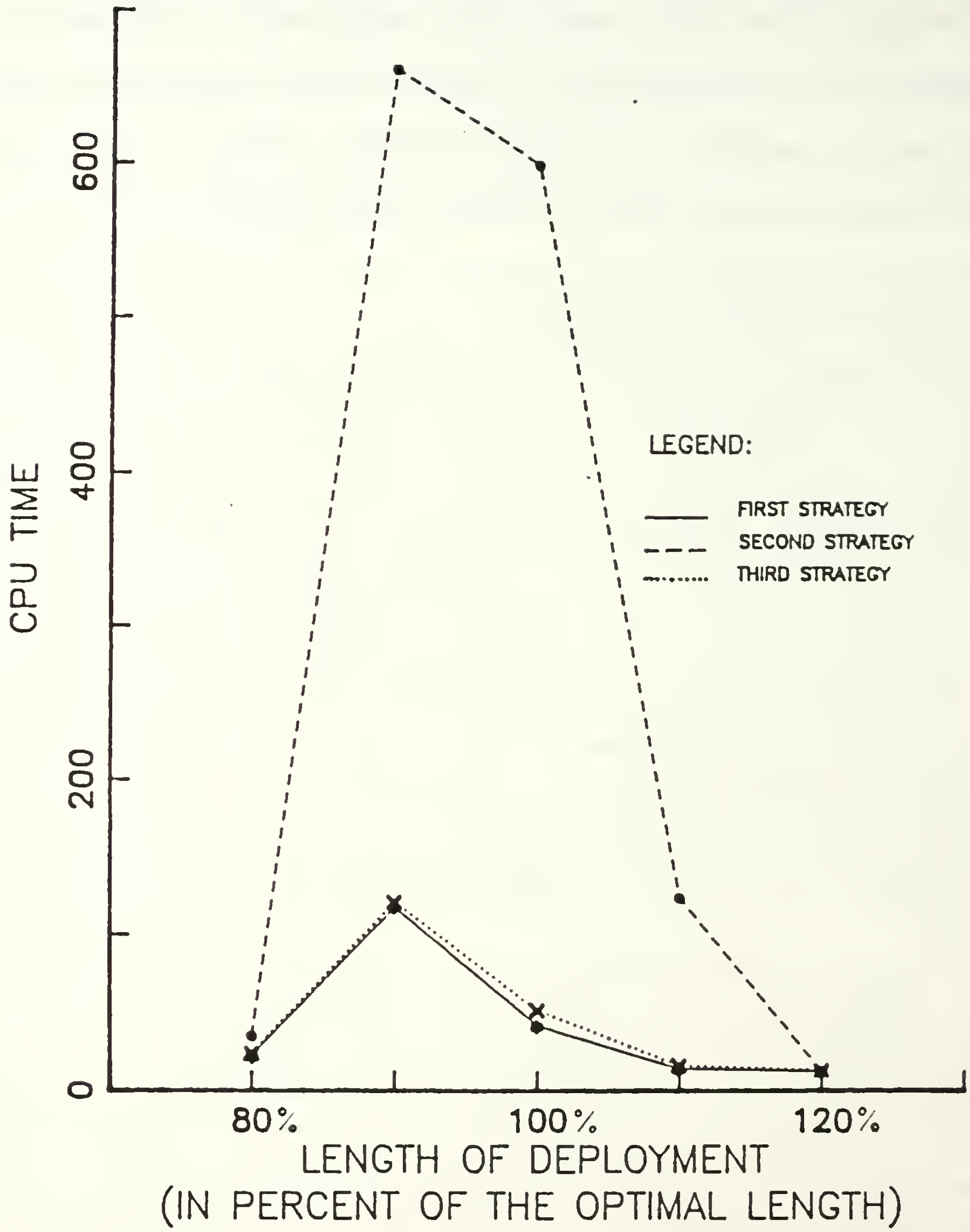

Figure 4.1 A Comparison of Three Strategies for Generating Schedules

One lower bound estimate is given by the following equation:

$$\tau_L = \text{integer part of } [(2*ntr - 1) * trmin + itmin]/spmax]$$

where

ntr = average number of cargoes (shiploads) per ship, i.e.,

$$ntr = \frac{\text{number of cargoes}}{\text{number of ships}},$$

trmin = the minimum travel distance between POD's,

itmin = the minimum distance between ships' initial positions and POE's, and

spmax = maximum speed among all ships.

To understand this bound, note that for each shipload assigned to a ship, the ship has to first deliver the shipload to its destination and return to pick up the next shipload on its schedule. Therefore, the ship has to make two trips (or ocean crossings) back and forth between POE's and POD's for each shipload, except for the last one for which the ship only has to make one trip from a POE to a POD. Thus, if ntr shiploads are assigned to one ship, it has to make (2*ntr - 1) trips. Since the minimum distance between a POE and a POD is trmin, the minimum total distance traveled by each ship is (2*ntr - 1) * trmin + itmin. The first term represents the distance for trips

between POE's and POD's and the second term represents the distance from ship's initial position to the first POE. Then, dividing the total by the maximum speed among the ships gives a lower bound for the optimal τ. Table 4.4 displays the value of the lower bound estimate and the correspond values of τ^*, the optimal duration, for 35 problems. On the average, τ_L underestimates τ^* by 40 %.

If historical data, e.g., data from previous deployment exercises, are available, the lower bound estimate τ_L can be improved by using linear regression. For example, using the data from Table 4.4, we obtain the following linear equation

$$\tau_{est} = 15.57 + 0.8 * \tau_L$$

where τ_{est} represent the linear estimate of τ^* based on τ_L. Figure 4.2 displays the linear estimate of τ^* graphically. Since linear regression minimizes the squared error, some τ_{est} naturally overestimates τ^*. Based on τ_L and τ_{est}, we implemented the following search algorithm for τ^*.

In the algorithm below, the initial estimate, τ_1, of the optimal duration, τ^*, is obtained by taking a convex combination of the lower bound and the linear regression estimates. It is assumed that the convex weight α, is chosen so that τ_1 underestimates τ^*. (Note that this is always possible by letting α equals one.) The parameter δ equals one time unit which is one day in all our examples.

TABLE 4.4

LIST THE LOWER BOUND ESTIMATES AND ACTUAL VALUES

OF OPTIMAL τ

PROBLEM NUMBER	NUMBER OF SHIPLOADS	NUMBER OF SHIPS	τ_L	τ_*
1	5	2	17	33
2	8	3	17	33
3	8	3	21	35
4	8	4	18	23
5	8	5	12	23
6	9	3	29	33
7	12	3	40	47
8	12	4	29	34
9	12	5	21	34
10	15	4	29	47
11	15	5	29	35
12	15	7	17	30
13	16	5	29	42
14	17	6	17	34
15	17	8	17	30
16	18	6	29	35
17	18	8	17	31
18	18	10	5	21
19	19	5	29	46
20	19	8	17	31
21	20	6	28	43
22	20	9	17	21
23	20	10	17	20
24	23	10	17	31
25	25	6	40	46
26	25	10	26	36
27	25	12	17	30
28	25	15	6	21
29	25	15	6	20
30	25	20	5	19
31	30	15	17	22
32	30	20	7	22
33	30	22	5	19
34	40	30	6	20
35	45	30	6	21

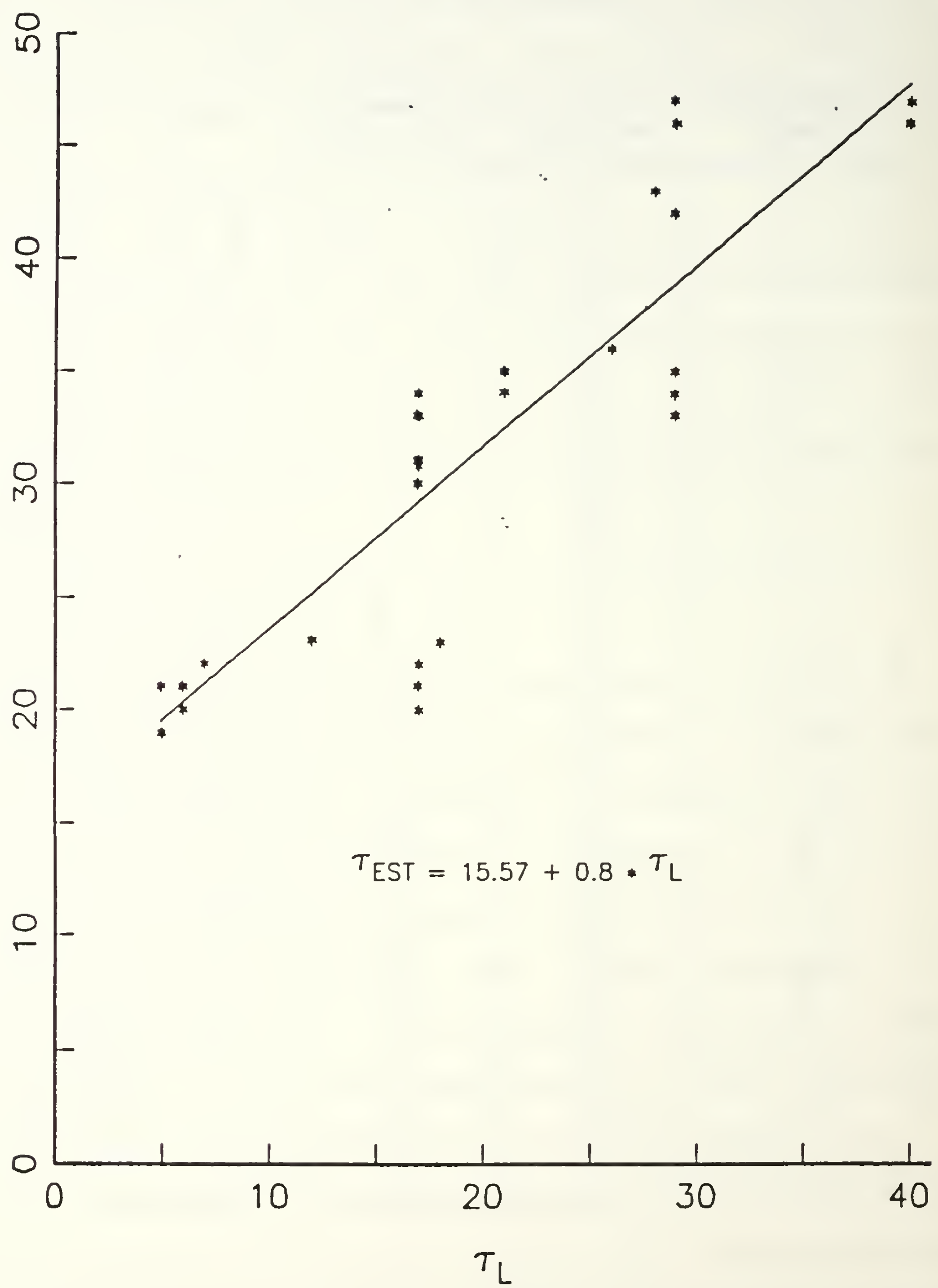

Figure 4.2 Lower Bound Estimate versus Actual Values of Optimal τ.

Algorithm

Step 0: Set $\tau_1 = \alpha * \tau_L + (1-\alpha) * \tau_{est}$ and set $k = 1$.

Step 1: Solve the feasibility-seeking problem, Problem $P3(\tau_k)$, by the column generation technique.

Step 2: If the optimal objective function value equals 0, stop; τ_k is optimal. Otherwise, set $\tau_{k+1} = \tau_k + \delta$ and $k = k + 1$. Go to step 1.

In Step 2, the current estimate, τ_k, of the optimal duration is increased by amount δ. In this manner, the current estimate τ_k approaches the optimal duration τ^* from below and all of the previously generated schedules remain feasible to the feasibility-seeking problems in the succeeding iterations. One topic for future research is to relax the assumption that τ_1 must underestimate τ^* and allow τ_k to be adjusted in either upward or downward direction in Step 2. Table 4.5 summarizes the computational results for the above algorithms. In all cases, the value for α is 0.7.

TABLE 4.5

COMPUTATIONAL RESULTS FOR THE COLUMN GENERATION TECHNIQUE

NUMBER OF SHIPLOADS	NUMBER OF SHIPS	RATIO	τ_1	OPTIMAL τ	CPU TIME
8	5	1.5	10	21	2.1
15	10	1.5	10	21	9.6
22	10	1.5	10	20	45.5
30	20	1.5	10	21	156.7
10	5	2.0	19	21	2.3
20	10	2.0	20	22	25.0
30	15	2.0	20	22	221.3
40	20	2.0	20	23	1216.2
12	5	2.5	20	33	7.9
25	10	2.5	20	33	86.1

D. PERCENTAGE OF INTEGER SOLUTIONS

Since the approach taken in solving the crisis deployment problem is the linear relaxation of the minimax set-partitioning problem, it is of interest to investigate the question concerning the integrality of the obtained results. In theory, the linear relaxation of the problem does not always produce an integer solution, in which case an integer programming algorithm such as the branch and bound method must be employed. However, Table 4.6 demonstrates that an integer programming algorithm is necessary for less than seven percent of the problems.

TABLE 4.6

NUMBER OF PROBLEMS WHICH TERMINATE WITH OPTIMAL INTEGER SOLUTIONS

τ	# OF PROBLEMS SOLVED	# OF PROBLEMS WITH INTEGER SOLUTIONS
$\geq 1.40*\tau^*$	39	32
$1.30*\tau^* - 1.39*\tau^*$	30	26
$1.20*\tau^* - 1.29*\tau^*$	35	33
$1.10*\tau^* - 1.19*\tau^*$	36	35
$1.00*\tau^* - 1.09*\tau^*$	74	74
Total	214	200 (93.45%)

V. CONCLUSIONS AND FUTURE STUDIES

This study formulates a crisis deployment problem as a set-partitioning problem with a minimax objective. An algorithm is developed for solving this problem. The idea underlying this algorithm is to solve the minimax set-partitioning by solving a sequence of simpler, but related, feasibility-seeking problems. Each time the feasibility-seeking problem produces a better solution for the minimax problem. The feasibility-seeking problem is similar in form to the minimax problem and both have a large number of columns. So to solve the feasibility-seeking problem, the column generation technique (as in the Dantzig-Wolfe decomposition method) is employed. The computational results in Chapter IV verify that this method is effective.

An important by-product of the above development is that the feasibility-seeking problem can also answer the question: Can all cargoes be deployed to their final destinations in τ days? A negative answer to this question leads to two natural follow-up questions which provide interesting areas for future studies:

1. How many additional ships are required to deploy all cargoes in τ days?
2. If no additional ship is available, which cargoes must be left behind?

Besides the above areas and the one mentioned in Chapter IV, the following areas are also worth studying.

1. The scenario considered in this study assume that the deployment is completed in one phase. In an extended period of conflicts, one may want deployment plans in several phases (waves).

2. Several embellishments to the current model are also possible.

    a. Allow the cargoes to arrive at the ports within time windows. The current model assumes that all cargoes are always available for transport.

    b. Allow cargoes in partial shiploads and in compatibility among cargoes, e.g., ammunition should not be loaded on same ship with fuel.

    c. Allow for nondeterministic delays in the completion times. These delays are due to unfavorable weather and/or enemy blockade.

APPENDIX

FORTRAN PROGRAM

```
*****************************************************************
*                                                               *
*                                                               *
*                   ====================                        *
*                   =  PROGRAM DEPLOY  =                        *
*                   ====================                        *
*                                                               *
*                                                               *
*                                                               *
* Date :       23 / 08 / 1988                                   *
*                                                               *
*                                                               *
*                                                               *
* Key variables :                                               *
*                                                               *
*   M      - number of constraints;                             *
*   N      - number of variables;                               *
*   A      - real matrix of dimension M by N containing         *
*            the coefficients of the M constraints;             *
*   B      - real vector of length M containing the right       *
*            hand sides of the constraints;                     *
*   C      - real vector of length N containing the             *
```

```
*           coefficients of the objective function;       *
*   XB     - basic variables;                             *
*   BINV   - matrix of dimension M by M corresponding to  *
*           the inverse of the basic matrix;              *
*   IB     - set of indices corresponding to the basic    *
*           variables;                                    *
*   U      - dual variables;                              *
*   XTIME  - duration of the schedule;                    *
*   SEQ    - sequence of cargoes to pick up;              *
*   ELL    - index of the variable leaving the basis;     *
*   K      - index of the variable entering the basis;    *
*   SB     - search direction;                            *
*   SIGB   - maximum feasible step size;                  *
*   SHIP   - ship number;                                 *
*   OBJ    - objective function value;                    *
*   MR     - movement requirements;                       *
*   IT     - travel distances from current ship ports to  *
*           POEs (ports of embarkation);                  *
*   TR     - travel distances between POEs and PODs       *
*           (ports of disembarkation);                    *
*   SPD    - ship speed;                                  *
*   TAU    - number of days to complete the deployment;   *
*   COMPAT - matrix of dimensions M by M that contains in- *
*           formation about the compatibility ship-cargo. *
*                                                         *
```

```
* Subroutines :                                                 *
*    The subroutines and their objectives are:                  *
*    - SIMPLX - solves the revised simplex method;              *
*    - RSTEP1 - step 1 of the revised simplex method;           *
*    - RSTEP2 - step 2 of the revised simplex method;           *
*    - RSTEP3 - step 3 of the revised simplex method;           *
*    - PHIPRM - updates the "B" inverse matrix;                 *
*    - RINVRT - inverts the B matrix;                           *
*    - RDAYS  - estimates an initial value for the number       *
*               of days to complete the deployment;             *
*    - SUBPR  - generates feasible schedules;                   *
*    - RTIME  - computes travel times.                          *
*    - RESULT - writes the output.                              *
*                                                               *
* Key parameters :                                              *
*    NLOA   - number of full shiploads of cargoes;              *
*    NSH    - number of ships;                                  *
*    NPOE   - number of ports of embarkation;                   *
*    NPOD   - number of ports of disembarkation;                *
*                                                               *
* Output :  The output provides the following information:      *
*    - objective function value,                                *
*    - number of simplex iterations,                            *
*    - optimal (minimum) number of days to complete the         *
*      deployment,                                              *
*    - optimal primal solution,                                 *
```

```
*    - optimal dual solution,                                 *
*    - ships' schedules,                                      *
*    - sequence of cargos to pick up per ship, and            *
*    - schedules' durations.                                  *
*                                                             *
* Input / Output  devices :                                   *
*    Disk (MOVREQ  DATA)  input   -  device 07                *
*    Disk (TRAVEL  DATA)  input   -  device 08                *
*    Disk (FSTDST  DATA)  input   -  device 09                *
*    Disk (COMPAT  DATA)  input   -  device 11                *
*    Disk (SPD     DATA)  input   -  device 12                *
*    Disk (DEPLOUT DATA)  output  -  device 10                *
*                                                             *
*                                                             *
***************************************************************


C  MAIN PROGRAM
*-------------------------------------------------------------*
*  The master problem.                                        *
*-------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER( MM = 100, NN = 2000, KK = 2 )
      DIMENSION B(MM),C(NN),SB(MM),U(MM),BINV(MM,MM),IB(MM),
     &WORK(MM),XB(MM),XCOL(MM),MR(100,KK),SPD(MM)
      REAL A(MM,NN),TR(15,15),IT(30,15)
```

```
      INTEGER MR,SHIP,XTIME(NN),SEQ(NN,MM),TAU,TAUL,TAUEST,
     &LSEQ(NN),NLOA,NSH,NPOE,NPOD,CTSHIP
      LOGICAL COMPAT(MM,MM)
      CHARACTER*13 MOVREQ,TRAVEL,FSTTIM
      COMMON /UNITS/ NIN, NOUT

C
C Initialize variables.
C
      DATA NLOA,NSH,NPOE,NPOD /  3, 2, 5, 5 /
      DATA A,B,C,XB,BINV / 200000*0.,100*1.D0,2000*0.D0,
     &100*1.0D0,10000*0.0D0 /
      DATA SB,WORK,U,IB /100*0.D0,100*0.D0,100*0.D0,100*0/
      DATA SEQ, LSEQ ,SPD / 200000*0,2000*0,100*0.0D0 /
      DATA MR,TR,IT,XTIME /200*0,225*0.,450*0.,2000*0 /
      NIN = 2
      NOUT = 6
      JOUT = 0
      TAU  = 1
      TAUL = 1
      TAUEST = 1

C
C  Read the data from the data files.
C
```

```
      READ(07,*)((MR(I,J),J=1,2),I=1,NLOA)
      READ(08,*)((TR(I,J),J=1,NPOD),I=1,NPOE)
      READ(09,*)((IT(I,J),J=1,NPOE),I=1,NSH)
      READ(11,*)((COMPAT(I,J),J=1,NSH),I=1,NLOA)
      READ(12,*)(SPD(I),I=1,NSH)

C
C  Estimate an initial value for TAU.
C

     CALL RDAYS(NLOA,NPOE,NPOD,NSH,TAU,TAUL,TAUEST,SPD,
    &TR,IT)
     MD = TAU

     WRITE(NOUT,8000) NLOA,NSH,NPOE,NPOD,TAU
     WRITE(NOUT,8030) TAUL,TAUEST

C
C  Convert input to number of columns (M) and number of
C  rows (N) in the "A" matrix.
C
     M = NLOA + NSH
     ITER = 0
```

```
5000  DO 10 I = 1,MM
         B(I) = 1.0D0
         SB(I) = 0.0D0
         U(I) = 0.0D0
         IB(I) = 0
         WORK(I) = 0.0D0
         XB(I) = 1.0D0
         XCOL(I) = 0.0D0
         DO 20 J = 1,NN
            C(J) = 0.0D0
            XTIME(J) = 0
            A(I,J) = 0.
            SEQ(J,I) = 0
            LSEQ(J) = 0
20       CONTINUE
         DO 30 K=1,MM
             BINV(I,K) = 0.D0
30       CONTINUE
10    CONTINUE
      CTSHIP = 0
      SHIP = 0
      K = 0
      N = 2*NLOA + NSH

C
C  Generate input for the revised simplex method.
```

```
C
      DO 40 I = 1,M
         IB(I) = I
         DO 50 J = 1,M
            IF (I .EQ. J) BINV(I,J) = 1.D0
50       CONTINUE
40    CONTINUE
      DO 60 I = 1,M-NSH
          C(I) = 1.0D0
60    CONTINUE

C
C  Generate artificial variables.
C
      DO 70 J = 1,M
         DO 80 K = 1,M
            IF (J .EQ. K) A(J,K) = 1.
80       CONTINUE
70    CONTINUE

C
C  Generate surplus variables.
C
      DO 90 J = 1,M
         DO 100 K = M+1,2*M-NSH
```

```
           IF(( J .EQ. (K-M) ) .AND. ( J .LE. (M-NSH) ))
     &     A(J,K)= -1.
100        CONTINUE
90      CONTINUE

        SUM = 0.D0
        DO 110 I=1,M
           U(I) = -C(I)
           SUM = SUM + C(IB(I))*XB(I)
110     CONTINUE
        OBJ = SUM
1000    CONTINUE

C
C  Strategy to choose for which ship the next schedule
C  will be generated
C
        SHIP  = SHIP + 1
        IF ( SHIP .EQ. NSH + 1 ) SHIP = 1

C
C  Generate  columns as needed by the master problem.
C
        CALL SUBPR(U,XCOL,TAU,M,N,NLOA,NPOE,NPOD,NSH,MR,TR,
     &IT,A,COMPAT,IB,XB,SHIP,XTIME,K,SPD,SEQ,LSEQ,CTSHIP)
        DO 120 I = 1, M
```

```
          SUM = 0.0D0
          DO 130 J = 1, M
              SUM = SUM + BINV(I,J)*A(J,K)
130       CONTINUE
          SB(I) = SUM
120    CONTINUE

C
C  Perform the revised simplex method.
C
       CALL SIMPLX(A,B,C,XB,BINV,SB,U,WORK,IB,OBJ,N,M,JOUT,
      &K,ITER)
       IF (OBJ .LT. 10.0D-4) THEN
           IF(TAU .EQ. MD) THEN
             MD = MD + 10
             TAU = TAUL
             GO TO 5000
           END IF
           NT = 1
           DO 140 I = 1,M
             IF(XB(I) .GT. 1.0D-3 .AND. XB(I) .LT. .9 ) NT=0
140        CONTINUE
           WRITE(NOUT,8010) NT
           IF(NT .EQ. 1) THEN
             GO TO 1100
           ELSE
```

```
          IF(ITER .GT. 4000) STOP
          GO TO 5000
        END IF
      END IF

      GO TO 1000

C
C  Write the results.
C
1100  WRITE(NOUT,8020) TAU
      CALL RESULT(JOUT,XB,U,C,A,IB,M,N,OBJ,ITER,SEQ,LSEQ,
     &XTIME,NSH,NLOA)

8000  FORMAT(20X,'PROGRAM OUTPUT',/,20X,'==============',
     &//,6X,I2,1X,'SHIPLOADS',3X,I2,1X,'SHIPS',3X,I2,
     &1X,'POES',3X,I2,1X,'PODS',/,6X,'INITIAL ESTIMATED',
     &'VALUE = TAU1 = ',I2,//)
8010  FORMAT(6X,'NT =',I2)
8020  FORMAT(6X,'*** FINAL (OPTIMAL) TAU = ',I2)
8030  FORMAT(6X,'** TAUL = ',I2,2X,', TAUEST = ',I2)
      STOP
      END
      SUBROUTINE SIMPLX (A,B,C,XB,BINV,SB,U,WORK,IB,OBJ,
     &N,M,JOUT,K,ITER)
*------------------------------------------------------------*
```

```
*  This subroutine performs the revised simplex method.     *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER( MM = 100, NN = 2000 )
      DIMENSION XB(MM),B(MM),C(NN),BINV(MM,MM),SB(MM),
     &U(MM),WORK(MM),IB(MM)
      REAL A(MM,NN)
      INTEGER ELL,XTIME(NN)
      COMMON /UNITS/ NIN, NOUT

      JOUT = 0

200   CONTINUE
C
      ITER = ITER + 1
      IF ( JOUT .EQ. 1 ) RETURN

      CALL RSTEP2(XB,SB,SIGB,ELL,M,JOUT)
      IF ( JOUT .EQ. 2 ) RETURN

      CALL RSTEP3(XB,C,B,BINV,A,WORK,OBJ,IB,ELL,K,N,M,ITER)
      IF (OBJ .LT. 10.0D-4) THEN
          NT = 1
          DO 10 I = 1,M
            IF(XB(I) .GT. 1.0D-3 .AND. XB(I) .LT. .90 ) NT=0
```

```
10        CONTINUE
          IF(NT .EQ. 1) THEN
            ITER = ITER + 1
            RETURN
          END IF
      END IF

      IF( MOD(ITER,10) .EQ. 0 ) CALL RINVRT(BINV,A,IB,
     &WORK,M,N)

      CALL RSTEP1(A,C,SB,U,BINV,IB,N,M,K,JOUT)

      GO TO 200
      END


      SUBROUTINE RSTEP1 (A,C,SB,U,BINV,IB,N,M,K,JOUT)
*------------------------------------------------------------*
*  This subroutine performs the step one of the revised      *
*  simplex method                                            *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER( MM = 100, NN = 2000 )
      DIMENSION C(NN),SB(MM),U(MM),BINV(MM,MM),IB(MM)
      REAL A(MM,NN)
```

```
      INTEGER XTIME(NN)
      COMMON /UNITS/ NIN, NOUT
C
      TOLCON = 1.D-6
      JOUT = 0
C
C  Compute the duals.
C
      DO 10 J=1,M
         SUM = 0.D0
         DO 20 I=1,M
            SUM = SUM + BINV(I,J)*C(IB(I))
20       CONTINUE
10    U(J) = - SUM
C
      K = 0
      VKMIN = 1.D30
C
      DO 50 I=1,N
C
C  Check if I is in IB.
C
         DO 30 J=1,M
            IF( I .EQ. IB(J) ) GO TO 50
30       CONTINUE
         SUM = C(I)
```

```
            DO 40 J=1,M
                SUM = SUM + A(J,I)*U(J)
40          CONTINUE
            IF(SUM .GE. VKMIN) GO TO 50
            VKMIN = SUM
            K = I
50       CONTINUE

         IF(VKMIN .LE. -TOLCON) GO TO 60
         JOUT = 1
         RETURN
60       CONTINUE

C
C  Form SB.
C
         DO 80 I=1,M
            SUM = 0.D0
            DO 70 J=1,M
           SUM = SUM + BINV(I,J)*A(J,K)
70         CONTINUE
80       SB(I) = SUM
         RETURN
         END
```

```
      SUBROUTINE RSTEP2 (XB,SB,SIGB,ELL,M,JOUT)
*------------------------------------------------------------*
*  This subroutine performs the step two of the revised     *
*  simplex method                                            *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER( MM = 100, NN = 2000 )
      DIMENSION XB(MM),SB(MM)
      INTEGER ELL
      COMMON /UNITS/ NIN, NOUT


      EPS = 1.D-6
      ELL = 0
      SIGB = 1.D30
      DO 100 I=1,M
          IF(SB(I) .LT. EPS) GO TO 100
          RATIO = XB(I)/SB(I)
          IF(RATIO .GE. SIGB) GO TO 100
          SIGB = RATIO
          ELL = I
100   CONTINUE
      IF(ELL .EQ. 0) JOUT = 2
      RETURN
      END
```

```
      SUBROUTINE RSTEP3 (XB,C,B,BINV,A,WORK,OBJ,IB,ELL,K,
     &N,M,ITER)
*-------------------------------------------------------------*
* This subroutine performs the step three of the revised     *
* simplex method                                              *
*-------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER( MM = 100, NN = 2000)
      DIMENSION C(NN),XB(MM),B(MM),BINV(MM,MM),WORK(MM)
      REAL A(MM,NN)
      INTEGER ELL,IB(MM)
      COMMON /UNITS/ NIN, NOUT

      DO 10 I=1,M
10    WORK(I) = A(I,K)
      CALL PHIPRM(BINV,WORK,ELL,M)
      DO 30 I=1,M
          SUM = 0.D0
          DO 20 J = 1,M
              SUM = SUM + BINV(I,J)*B(J)
20        CONTINUE
          XB(I) = SUM
30    CONTINUE
      IB(ELL) = K
      SUM = 0.D0
```

```
      DO 40 I = 1,M
          SUM = SUM + C(IB(I))*XB(I)
40    CONTINUE
      OBJ = SUM
      RETURN
      END


      SUBROUTINE PHIPRM(BINV,WORK,ELL,M)
*------------------------------------------------------------*
*  This subroutine updates the BINV matrix.                  *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER (I-N)
      PARAMETER( MM =100, NN = 2000 )
      DIMENSION BINV(MM,MM),WORK(MM)
      INTEGER ELL
      COMMON /UNITS/ NIN, NOUT

      TOL = 1.D-6
      SUM = 0.D0
      DO 10 I = 1,M
          SUM = SUM + BINV(ELL,I)*WORK(I)
10    CONTINUE
      YSUM = DABS(SUM)
      IF(YSUM .GE. TOL) GO TO 20
```

```
      WRITE(NOUT,8000) SUM
      STOP
20    CONTINUE
      SUM = 1.D0/SUM
      DO 30 I = 1,M
          BINV(ELL,I) = SUM*BINV(ELL,I)
          IF( (BINV(ELL,I) .LT. TOL) .AND. (BINV(ELL,I)
     &    .GT. -TOL) ) BINV(ELL,I) = 0.0D0
30    CONTINUE
      DO 60 J = 1,M
          IF(J .EQ. ELL) GO TO 60
          TEMP = 0.D0
          DO 40 I = 1,M
              TEMP = TEMP + BINV(J,I)*WORK(I)
40        CONTINUE
          IF( (TEMP .LT. TOL) .AND. (TEMP .GT. -TOL) )
     &    TEMP = 0.0D0
          DO 50 I = 1,M
              BINV(J,I) = BINV(J,I) - TEMP*BINV(ELL,I)
              IF( (BINV(J,I) .LT. TOL) .AND. (BINV(J,I)
     &        .GT. -TOL) ) BINV(J,I) = 0.0D0
50       CONTINUE
60    CONTINUE
      RETURN
```

```
8000  FORMAT(6X,'**** ERROR **** NEW MATRIX WOULD BE',
     &' SINGULAR, INNER PRODUCT =',G15.6)
      END

      SUBROUTINE RINVRT (BINV,A,IB,WORK,M,N)
*------------------------------------------------------------*
*  This subroutine reinverts the basis.                      *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER(I-N)
      PARAMETER ( ZERO = 0.0D0, ONE = 1.0D0 )
      PARAMETER ( MM =100, NN = 2000 )
      DIMENSION BINV(MM,MM), IB(MM), OMAT(MM,MM), WORK(MM)
      REAL A(MM,NN)
      COMMON /UNITS/ NIN, NOUT

      TOL = 1.D-6
      DO 10 I = 1, M
         DO 20 J = 1, M
            BINV(I,J) = ZERO
            OMAT(I,J) = A(I,IB(J))
20       CONTINUE
         BINV(I,I) = ONE
10    CONTINUE

C
```

```
C  Locate maximum magnitude element on or below the main
C  diagonal.
C
         DO 30 K = 1, M
            IF ( K .LT. M) THEN
               IMAX = K
               AMAX = DABS(OMAT(K,K))
               KP1 = K+1
               DO 40 I = KP1, M
                   IF ( AMAX .LT. DABS(OMAT(I,K))) THEN
                      IMAX = I
                      AMAX = DABS(OMAT(I,K))
                   ENDIF
40             CONTINUE
C
C  Interchange rows IMAX and K if IMAX is not equal to K
C
               IF (IMAX .NE. K) THEN
                  DO 50 J = 1, M
                      ATMP = OMAT(IMAX, J)
                      OMAT(IMAX, J) = OMAT(K,J)
                      OMAT(K,J) = ATMP
                      BTMP = BINV(IMAX,J)
                      BINV(IMAX,J) = BINV(K,J)
                      BINV(K,J) = BTMP
```

```
50                CONTINUE
              ENDIF
          ENDIF

C
C  Test for singular matrix.
C
          IF (DABS(OMAT(K,K)) .LT. 1.0D-6) THEN
              WRITE(NOUT,8000) K, OMAT(K,K)
          ELSE
              DIV = OMAT(K,K)
              DO 60 J = 1, M
                  OMAT(K,J) = OMAT(K,J)/DIV
                  IF( (OMAT(K,J) .LT. TOL) .AND. (OMAT(K,J)
     &            .GT. -TOL) ) OMAT(K,J) = 0.0D0
                  BINV(K,J) = BINV(K,J)/DIV
                  IF( (BINV(K,J) .LT. TOL) .AND. (BINV(K,J)
     &            .GT. -TOL) ) BINV(K,J) = 0.0D0
60            CONTINUE
              DO 70 I = 1, M
                   AMULT = OMAT(I,K)
                   IF( (AMULT .LT. TOL) .AND. (AMULT
     &             .GT. -TOL) ) AMULT = 0.0D0
                     IF ( I .NE. K) THEN
                        DO 80 J = 1, M
                            OMAT(I,J) = OMAT(I,J) - AMULT
```

```
     &                          * OMAT(K,J)
                                BINV(I,J) = BINV(I,J) - AMULT
     &                          * BINV(K,J)
                                IF( (BINV(I,J) .LT. TOL) .AND.
     &                          (BINV(I,J) .GT. -TOL ) )
     &                          BINV(I,J) = 0.0D0
80                          CONTINUE
                         ENDIF
70                 CONTINUE
                ENDIF
30    CONTINUE
8000  FORMAT(' * ERROR: BASIS IS SINGULAR',I4,D15.6)
      RETURN
      END


      SUBROUTINE SUBPR (U,XCOL,TAU,M,N,NLOA,NPOE,NPOD,NSH,
     &MR,TR,IT,A,COMPAT,IB,XB,SHIP,XTIME,K,SPD,SEQ,LSEQ,
     &CTSHIP)
*------------------------------------------------------------*
*  This subroutine generates feasible (acceptable) columns *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION (A-H,O-Z), INTEGER (I-N)
      PARAMETER( MM = 100, NN = 2000, KK = 2, JJ = 2000 )
      DIMENSION XCOL(MM),U(MM),UU(MM),V(MM),XB(MM),SA(MM),
     &IB(MM),SPD(MM)
```

```
      REAL A(MM,NN),TR(15,15),IT(30,15)
      INTEGER VIND(MM),PRED(0:JJ),LOAD(0:JJ),TIME(0:JJ),
     & MR(100,KK),FROLD,TOLD,PATH(0:MM),CURLD,COUNT,
     & LENGTH,LASTND,SHIP,TT,MLNGTH,XTIME(NN),CTSHIP,
     & CTSON(0:MM),LSEQ(NN),TAU,STACK(0:JJ),TOP,
     & SEQ(NN,MM),CTBACK(0:MM)
      LOGICAL COMPAT(MM,MM)
      DOUBLE PRECISION MIN,MINRC
      COMMON /UNITS/ NIN,NOUT


C
C  Initialize the variables.
C
      LIMIT = N
1000  CTSHIP = 0
2000  DO 10 I = 1,MM
          SA(I) = 0.0D0
          UU(I) = 0.D0
          V(I) = 0.D0
          VIND(I) = 0
10    CONTINUE
      NNEG = NLOA
      MINRC = 0.0D0


C
C  Sort the duals.
```

```
C
      DO 20 I = 1,NLOA
          UU(I) = U(I)
20    CONTINUE
      IF( N .GE. (2*NLOA + NSH + 1) ) THEN
         DO 30 I = 1,M
            DO 40 J = 1,M
               IF( (IB(J) .GT. (2*NLOA + NSH)) .AND.
     &             (A((NLOA + SHIP),IB(J)) .NE. 1.D0) .AND.
     &             (XB(J) .GT. 0.5D0) ) THEN
                  SA(I) = SA(I) + A(I,IB(J))
               END IF
40          CONTINUE
            IF( SA(I) .LT. 1.0D0 ) UU(I) = -2.0D0
30       CONTINUE
      END IF
C
C  Check ship-cargo and ship-port compatibility.
C
      DO 50 I = 1,NLOA
          IF( .NOT. COMPAT(I,SHIP)  ) UU(I) = 99.0D0
50    CONTINUE
      DO 60 I = 1,NLOA
          MIN = 0.1D-6
          COUNT = 0
          IND = 0
```

```
          DO 70 J = 1,NLOA
              IF( UU(J) .LT. MIN ) THEN
                  MIN = UU(J)
                  IND = J
                  COUNT = 1
              END IF
70        CONTINUE

              IF( COUNT .EQ. 0 ) THEN
                  NNEG = I - 1
                  GO TO 4000
              END IF
            V(I) = MIN
            VIND(I) = IND
            UU(IND) = 99.0D0
60    CONTINUE

4000  CONTINUE

C
C  The Modified Depth First Search Algorithm.
C

C
C  Create all nodes out of the source and include them
C  in a stack.
```

```
C
      DO 80 I = 0,JJ - 1
          TIME(I) = 0
          STACK(I) = 0
          LOAD(I) = 0
          PRED(I) = 0
80    CONTINUE

      DO 90 I = 1,MM
          XCOL(I) = 0.D0
          PATH(I-1) = 0
          CTBACK(I-1) = 0
          CTSON(I-1) = 0
90    CONTINUE
      LENGTH = 0
      LASTND = 1
      TOP = 0
      CURLD = 0
      FROLD = 0
      TOLD = 0
      DO 100 I = NNEG,1,-1
          LOAD(NNEG - I + 2) = VIND(I)
          PRED(NNEG - I + 2) = 1
          STACK(NNEG - I + 1) = (NNEG - I + 2)
          TOP = TOP + 1
          LASTND = LASTND + 1
```

```
100   CONTINUE

C
C  Main loop to search for feasible schedules.
C
3000  CURLD = STACK(TOP)
      IF( LENGTH .EQ. NNEG ) THEN
          RCOST = 0.0D0
          DO 110 I = 1,LENGTH
              XCOL(LOAD(PATH(I))) = 1.0D0
110       CONTINUE
          XCOL(NLOA + SHIP) = 1.0D0
          DO 120 I = 1,M
              IF( XCOL(I) .EQ. 1.0D0 ) RCOST = RCOST + U(I)
120       CONTINUE
          IF(RCOST .GT. -1.0D-4) RCOST = 0.0D0
          IF( (RCOST .LT. 0.0D0) ) THEN
               N = N+1
               DO 130 I = 1,M
                   A(I,N) = XCOL(I)
130            CONTINUE
               XTIME(N) = TIME(PRED(CURLD))
               DO 140 J = 1,LENGTH
                   SEQ(N,J) = LOAD(PATH(J))
140            CONTINUE
               LSEQ(N) = LENGTH
```

```
          RETURN
       END IF
     END IF
     IF( CURLD .EQ. 0 ) THEN
        IF( MINRC .LT. 0.0D0 ) RETURN
        CTSHIP = CTSHIP + 1
        SHIP = SHIP + 1
        IF(SHIP .GT. NSH) SHIP = 1
        IF( CTSHIP .EQ. NSH ) THEN
           WRITE(NOUT,8000)
           TAU = TAU + 1
           WRITE(NOUT,8010) TAU
           GO TO 1000
        END IF
        GO TO 2000
     END IF

   TOP = TOP - 1
       IF( N .GE. NN ) STOP 'RUN OUT OF SPACE'

   IF( PRED(CURLD) .EQ. 1) THEN
       LASTND = LASTND - LENGTH
       LENGTH = 0
   END IF
```

```
      IF( CTSON(LENGTH) .EQ. CTBACK(LENGTH) ) THEN
           DO 150 I = 1,LENGTH
               IF( PRED(CURLD) .EQ. PATH(I) )  THEN
                   LASTND = LASTND - LENGTH + I
                   LENGTH = I
                   GO TO 5000
               END IF
150        CONTINUE
      END IF


5000   PATH(LENGTH + 1) = CURLD

C
C  Compute the travel time to pick up another cargo.
C
      FROLD = LOAD(PRED(CURLD))
      TOLD = LOAD(CURLD)
      TT = 0
      CALL RTIME(NPOE,NPOD,MR,TR,IT,FROLD,TOLD,SHIP,NSH,
     &NLOA,TT,SPD)
      TIME(CURLD) = TIME(PRED(CURLD)) + TT

C
C  Verify if it is feasible to pick up another cargo.
C
```

```
      IF( TIME(CURLD) .LE. TAU ) THEN
      CTBACK(LENGTH) = CTBACK(LENGTH) + 1
      LENGTH = LENGTH + 1
      CTSON(LENGTH) = 0
          DO 160 I = NNEG,1,-1
              DO 170 J = 1,LENGTH
                IF( VIND(I) .EQ. LOAD(PATH(J)) ) GO TO 160
170           CONTINUE
              LASTND = LASTND + 1
              LOAD(LASTND) = VIND(I)
              PRED(LASTND) = CURLD
              TOP = TOP + 1
              CTSON(LENGTH) = CTSON(LENGTH) + 1
160       CONTINUE
          DO 180 I = LASTND,(LASTND - CTSON(LENGTH)+1),-1
              STACK(TOP) = I
              TOP = TOP - 1
180       CONTINUE
          TOP = TOP + CTSON(LENGTH)
      ELSE
          LASTND = LASTND - 1
          RCOST = 0.0D0
          DO 190 I = 1,LENGTH
              XCOL(LOAD(PATH(I))) = 1.0D0
190       CONTINUE
          XCOL(NLOA + SHIP) = 1.0D0
```

```
      DO 200 I = 1,M
          IF( XCOL(I) .EQ. 1.0D0 ) RCOST = RCOST + U(I)
200   CONTINUE
      IF(RCOST .GT. -1.0D-4) RCOST = 0.0D0
      IF( RCOST .LT. 0.0D0 .AND. LENGTH .GT.
    & INT(NLOA/NSH)-1 ) THEN
          IF ( CTBACK(LENGTH) .EQ. 0 ) THEN
              N = N + 1
              DO 210 I = 1,M
                  A(I,N) = XCOL(I)
210           CONTINUE
              XTIME(N) = TIME(PRED(CURLD))
              DO 220 J = 1,LENGTH
                  SEQ(N,J) = LOAD(PATH(J))
220           CONTINUE
              LSEQ(N) = LENGTH
              IF( RCOST .LT. MINRC ) THEN
                  MINRC = RCOST
                  K = N
              END IF
          END IF
          DO 230 I = 1,LENGTH
              XCOL(LOAD(PATH(I))) = 0.0D0
              XCOL(NLOA + SHIP) = 0.0D0
230       CONTINUE
      ELSE
```

```
            DO 240 I = 1,LENGTH
                XCOL(LOAD(PATH(I))) = 0.0D0
240         CONTINUE
            XCOL(NLOA + SHIP) = 0.0D0
        END IF
        CTBACK(LENGTH) = CTBACK(LENGTH) + 1
        GO TO 3000
      END IF
      IF( N .GE. LIMIT + 1 ) RETURN
      CTBACK(LENGTH) = 0
      GO TO 3000

8000  FORMAT(//,6X,'TAU NOT FEASIBLE, INCREASE TAU ')
8010  FORMAT(/,6X,'NEW TAU = ',I4)
      END

      SUBROUTINE RTIME (NPOE,NPOD,MR,TR,IT,FROLD,TOLD,SHIP,
     &NSH,NLOA,TT,SPD)
*------------------------------------------------------------*
*  This subroutine calculates travel times.                  *
*------------------------------------------------------------*
       IMPLICIT DOUBLE PRECISION( A-H,O-Z ), INTEGER( I-N )
       PARAMETER( KK = 2, MM = 100, NN = 2000 )
       DIMENSION SPD(MM)
       REAL IT(30,15),TR(15,15)
       INTEGER MR(100,KK),TT,TOLD,SHIP,FROLD
```

```
      TT = 0

C Calculating the travel time.
      IF(FROLD .EQ. 0) THEN
        TT = IDNINT((IT(SHIP,MR(TOLD,1)) + TR(MR(TOLD,1),
     &         MR(TOLD,2))) / (24. * SPD(SHIP)))
      ELSE
        TT = IDNINT((TR(MR(TOLD,1),MR(FROLD,2)) +
    &         TR(MR(TOLD,1),MR(TOLD,2)))/(24. * SPD(SHIP)))
      END IF
      RETURN
      END


     SUBROUTINE RDAYS (NLOA,NPOE,NPOD,NSH,TAU,TAUL,
    &TAUEST,SPD,TR,IT)
*------------------------------------------------------------*
*  This subroutine calculates an initial estimate of the    *
*  number of days to complete the deployment.               *
*------------------------------------------------------------*
     PARAMETER ( MM = 100 )
     INTEGER NPOE,NPOD,TAU,TAUL,TAUEST,NLOA,NSH
     DIMENSION TR(15,15), IT(30,15)
     REAL TRMIN,IT,TR,ITMIN,SPMAX
```

```
      DOUBLE PRECISION SPD(MM)
      COMMON /UNITS/ NIN,NOUT

      TAU = 1
      TAUL = 1
      TAUEST = 1
C
C Calculate the minimum distance to travel.
C
      TRMIN = 99999999.
      DO 100 I=1,NPOE
         DO 200 J=1,NPOD
             IF(TR(I,J) .LT. TRMIN) TRMIN = TR(I,J)
200      CONTINUE
100   CONTINUE

C
C  Calculate the minimum travel distance from the initial
C  ships' locations to the POEs.
C
      ITMIN = 99999999.
      DO 300 I = 1,NSH
         DO 400 J = 1,NPOE
             IF(IT(I,J) .LT. ITMIN) ITMIN = IT(I,J)
400      CONTINUE
300   CONTINUE
```

```
C
C  Calculate the maximum traveling ships' speeds.
C
      SPMAX = -1.
      DO 600 J = 1,NSH
          IF(SPD(J) .GT. SPMAX) SPMAX = SPD(J)
600   CONTINUE

C
C  Compute the average number of trips per ship.
C
      NTR = NLOA / REAL(NSH)


C
C  Calculate an estimate for TAU.
C
      TAUL = INT((((NTR * 2) - 1) * TRMIN) + ITMIN) /
     &       (SPMAX*24.))
      TAUEST = INT(15.5 + ( 0.8 * TAUL ))
      TAU = INT( (0.7 * TAUL) + (0.3 * TAUEST) )

      RETURN
      END
```

```
      SUBROUTINE RESULT (JOUT,XB,U,C,A,IB,M,N,OBJ,ITER,
     &SEQ,LSEQ,XTIME,NSH,NLOA)
*------------------------------------------------------------*
*  This subroutine writes the solution to the output file  *
*------------------------------------------------------------*
      IMPLICIT DOUBLE PRECISION(A-H, O-Z), INTEGER(I-N)
      PARAMETER( MM =100, NN = 2000, ZERO = 0.0D0 )
      DIMENSION U(MM),C(NN),XB(MM),IB(MM)
      INTEGER SEQ(NN,MM),LSEQ(NN),XTIME(NN)
      REAL A(MM,NN)
      COMMON /UNITS/ NIN, NOUT

      IF(JOUT .GE. 2) GO TO 80
      WRITE(NOUT,8000) OBJ
      WRITE(NOUT,8005) ITER
      WRITE(NOUT,8010)


C
C  Is X(I) basic?
C
      DO 30 I=1,N
          DO 10 J=1,M
              INDEX = J
              IF(IB(J) .EQ. I) GO TO 20
10        CONTINUE
          GO TO 30
```

```
20        CONTINUE
          WRITE(NOUT,8020) I,XB(INDEX)
30    CONTINUE
      WRITE(NOUT,8030)
      WRITE(NOUT,8040) (I,U(I),I=1,NLOA)
      WRITE(NOUT,8050) (I,U(I),I=(NLOA+1),M)
      DO 70 I=1,N
         DO 40 J=1,M
            IF(IB(J) .EQ. I) THEN
                IF((XB(J) .GT. 1.D-2) .AND. (I .GT.
     &          2*NLOA+NSH)) THEN
                    DO 90 L=NLOA+1,M
                       IF( A(L,IB(J)) .GT. .9)
     &                 WRITE(NOUT,9010) (L-NLOA)
90                  CONTINUE
                    WRITE(NOUT,9020) (SEQ(IB(J),K),
     &              K = 1,LSEQ(IB(J)) )
                    WRITE(NOUT,8090) IB(J),XTIME(IB(J))
                END IF
                GO TO 60
            END IF
40       CONTINUE

C
C  X(I) is non basic.
C
```

```
         SUM = C(I)
         DO 50  J=1,M
            SUM = SUM + A(J,I)*U(J)
50       CONTINUE
         GO TO 70

C
C  X(I) is basic.
C
60    CONTINUE
70    CONTINUE
80    CONTINUE
      IF(JOUT .EQ. 2) WRITE(NOUT,8070)
      IF(JOUT .EQ. 3) WRITE(NOUT,8080)
      RETURN
C
8000  FORMAT(//,6X,'OPTIMAL OBJECTIVE FUNCTION VALUE IS',
     &F12.5)
8005  FORMAT(//,6X,'NUMBER OF ITERACTIONS = ',I5)
8010  FORMAT(//,17X,'OPTIMAL PRIMAL SOLUTION',/)
8020  FORMAT(18X,'X(',I3,') =',F14.7)
8030  FORMAT(//,18X,'OPTIMAL DUAL SOLUTION',/)
8040  FORMAT(18X,'U(',I2,') =',F14.7)
8050  FORMAT(18X,'V(',I2,') =',F14.7)
8070  FORMAT(//,6X,'PROBLEM IS UNBOUNDED FROM BELOW')
8080  FORMAT(//,6X,'PROBLEM HAS NO FEASIBLE SOLUTION')
```

```
8090  FORMAT(6X,'DURATION OF SCHEDULE ',I4,' IS : ',I3,/)
9010  FORMAT(/,6X,'SCHEDULE FOR SHIP : ',I2,/,6X,'CARGOES
     &TO CARRY:')
9020  FORMAT(6X,I4)
      END
```

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